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Protection Matching: A New Scheduling Rule for Improved Design of BICM-ID Systems

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***Abstract*—Bit-interleaved coded modulation with iterative decoding (BICM-ID) has been verified to be a powerful transmission scheme with remarkable bit-error-rate performance. Among those well-designed BICM-ID systems, we observe that some of the channel encoders and signal mappers are inherently with the capability of multilevel protection. A new scheduling rule called *protection matching* which can properly schedule the data flow between the channel encoder and signal mapper with respect to the multilevel protection capability is proposed to achieve further performance improvement. Not only theoretical analysis but also simulation results are given to verify the advantage of the proposed design.**

I. Introduction

Bit-interleaved coded modulation (BICM) is an efficient and powerful transmission scheme for fading channels [1][2]. Rich diversity can be obtained by BICM to beat the channel impairments with the aid of the bit-wise interleaver. However, such an interleaver also makes the optimal decoding of BICM infeasible. On account of the serially concatenation of the channel encoder and signal mapper, BICM with iterative decoding (BICM-ID) which iteratively exchanges the soft outputs between the demapper and decoder was proposed in [3][4] to improve the decoding performance. With a proper design of the channel code and signal mapper, BICM-ID has been shown to provide remarkable bit-error-rate (BER) performance for both of fading and non-fading channels with acceptable decoding complexity.

To find the optimal design of BICM-ID, most of the researches on performance analysis and design criteria are conducted from two viewpoints. One category of the studies are from the BER aspect, for which the pairwise error probability (PEP) is considered for developing various asymptotic bounds [3]-[6]. By assuming the uniform interleaving of coded bits prior to the signal mapper, their results suggest that the squared Euclidean distance (SED) and the harmonic mean distance between any two modulated sequences should be maximized for additive white Gaussian noise (AWGN) channels and Rayleigh fading channels, respectively; other variants of performance measurement are also provided for Rician and Nakagami fading channels. Due to the iterative nature of the BICM-ID receiver, the other category of the researches are based on the extrinsic information transfer (EXIT) chart [7][8] to explore the system design. In this approach, a series of studies in [9]-[13] reported that BICM-ID systems should be designed in a best way such that a tunnel between the decoder and demapper curves is opened at signal-to-noise ratio (SNR) as low as possible to guarantee a low threshold and both curves should intersect at a point with mutual information as high as possible to avoid the undesired error floor at high SNR.

Based on the above design guidelines, various BICM-ID systems have been proposed to achieve good BER performance. Among those well-designed systems, however, some of the channel encoders and signal mappers are inherently with the capability of multilevel protection. If the coded bits outputted from the channel encoder can be properly scheduled into different input streams of the signal mapper by a special rule called *protection matching* which requires that coded bits from the output streams of channel encoder with lower (higher) protection level can be only fed into the input streams of signal mapper with higher (lower) protection level, we observe that a further improvement in the BER performance can be obtained. In this paper, a general guideline is presented to incorporate the BICM-ID systems with the scheduling rule of protection matching. Not only theoretical analysis but also simulation results are given to verify the advantage of the proposed design.

The rest of this paper is organized as follows. In Section II, a brief review of BICM-ID systems and the related performance analysis is given. The concept of protection matching and the corresponding implementation guideline for BICM-ID systems are described in Section III. In Section IV, simulation results are provided for performance verification. Finally, a summary is drawn in Section V to conclude this work.

II. Review of BICM-ID Systems and Related Performance Analysis

A. System Model

In conventional BICM-ID systems, the transmitter comprises the serial concatenation of a channel encoder and a signal mapper with a bit-wise interleaver Π inserted between as shown in Fig. 1. The information bits are first encoded by the k-input n-output channel encoder to generate the coded sequence $\underline{c} = (\underline{c}_0, \underline{c}_1, \ldots, \underline{c}_t, \ldots)$, where $\underline{c}_t = (c_t^{(0)}, c_t^{(1)}, \ldots, c_t^{(n-1)})$ denote the coded bits at time t. $\underline{c}$ is then permuted by Π to obtain the interleaved sequence $\underline{v}$. Assume that the signal mapper is equipped with the constellation χ of M signal points $x_0, x_1, \ldots, x_{M-1}$ and the labeling function μ and $M = 2^m$ for some positive integer m without loss of generality. For each transmission, m consecutive bits $\underline{v}_t = (v_t^{(0)}, v_t^{(1)}, \ldots, v_t^{(m-1)})$ are selected from $\underline{v}$ and mapped to a modulated symbol $s_t \in \chi$ by μ, i.e., $s_t = \mu(\underline{v}_t)$. Let $\underline{s} = (s_0, s_1, \ldots, s_t, \ldots)$ be the modulated sequence corresponding to $\underline{v}$; we also denote $\underline{s} = \mu(\underline{v})$ for convenience.

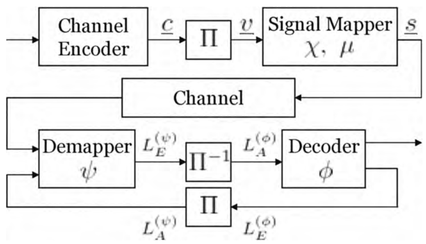

Fig. 1. Block diagram for conventional BICM-ID systems.

For an AWGN channel, the received signal corresponding to s_t can be represented by

$$y_t = s_t + n_t = \mu(\underline{v}_t) + n_t \tag{1}$$

where n_t denotes the Gaussian noise with zero mean and variance $N_0/2$ per dimension. At the receiver, the demapper ψ takes y_t and the priori inputs $L_A^{(\psi)}(v_t^{(i)})$'s, i.e., the log-likelihood rations (LLRs) of $v_t^{(i)}$'s feedback from the decoder ϕ, to compute the extrinsic outputs by [9]

$$\begin{aligned} L_E^{(\psi)}(v_t^{(i)}) &= \ln \frac{\Pr(v_t^{(i)}=0|y_t)}{\Pr(v_t^{(i)}=1|y_t)} - L_A^{(\psi)}(c_t^{(i)}) \\ &= \ln \frac{\sum_{x \in \chi_0^{(i)}} \exp\left\{ -\frac{|y_t - x|^2}{N_0} + \sum_{j \neq i} v_t^{(j)} L_A^{(\psi)}(v_t^{(j)}) \right\}}{\sum_{x \in \chi_1^{(i)}} \exp\left\{ -\frac{|y_t - x|^2}{N_0} + \sum_{j \neq i} v_t^{(j)} L_A^{(\psi)}(v_t^{(j)}) \right\}} \end{aligned} \tag{2}$$

where $\chi_b^{(i)}$ is the subset of χ containing all the signal points with the binary value b in the i-th bit position on their labels. The output LLRs of the demapper are then permuted by the deinterleaver Π^{-1} and serve as the priori inputs $L_A^{(\phi)}(v_t^{(i)})$'s of the decoder. Finally, the extrinsic outputs $L_E^{(\phi)}(v_t^{(i)})$'s of the decoder generated by an appropriate soft-input soft-output decoding algorithm, e.g., the BCJR algorithm [14], are feedback to the demapper for next iteration of decoding.

B. Performance Analysis of BICM-ID Systems

Previous works to characterize the performance of BICM-ID systems can be divided into two categories. One is from the error probability aspect and the other is based on the EXIT chart. Details of the above studies are described below.

1) BER Based Analysis: For BICM-ID systems, the bit error probability can be upper bounded by [3]

$$P_b \leq \frac{1}{k} \sum_{\underline{v}} \Pr(\underline{v}) \sum_{\hat{\underline{v}} \neq \underline{v}} \Pr(\mu(\underline{v}) \to \mu(\hat{\underline{v}})) B(\underline{v}, \hat{\underline{v}}) \tag{3}$$

where $\Pr(\underline{v})$ is the probability of transmitting $\underline{v}$, $\Pr(\mu(\underline{v}) \to \mu(\hat{\underline{v}}))$ denotes the PEP that the decoder decides in favor of $\mu(\hat{\underline{v}})$ than $\mu(\underline{v})$, and $B(\underline{v}, \hat{\underline{v}})$ represents the Hamming distance between the information sequences corresponding to $\underline{v}$ and $\hat{\underline{v}}$. Let $\underline{s} = \mu(\underline{v})$ and $\hat{\underline{s}} = \mu(\hat{\underline{v}})$. In AWGN channels, the PEP between $\underline{s}$ and $\hat{\underline{s}}$ can be evaluated by

$$\Pr(\underline{s} \to \hat{\underline{s}}) = Q\left(\sqrt{\frac{d_E^2(\underline{s}, \hat{\underline{s}})}{2N_0}}\right) \tag{4}$$

where $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-t^2} dt$ and $d_E^2(\underline{s}, \hat{\underline{s}})$ denotes the SED between $\underline{s}$ and $\hat{\underline{s}}$. To simplify the analysis of (4), the demapper is usually assumed to satisfy the error-free feedback (EFF) condition, i.e., $v_t^{(i)}$ is determined by assuming that ideal feedbacks of $v_t^{(0)}, \ldots, v_t^{(i-1)}, v_t^{(i+1)}, \ldots, v_t^{(m-1)}$ from the decoder are available [3]. By the EFF condition, the transmission of s_t based on χ and μ can be approximated as m independent transmissions of $v_t^{(0)}, v_t^{(1)}, \ldots, v_t^{(m-1)}$ with the appropriate binary modulation [4]. Thus, given χ and μ, the SED between $\underline{s}$ and $\hat{\underline{s}}$ can be lower bounded by [4]

$$d_E^2(\underline{s}, \hat{\underline{s}}) \geq \sum_{j=0}^{m-1} w_j d_j^2 \tag{5}$$

where d_j^2 denotes the squared intersignal Euclidean distance (SIED) for the j-th equivalent transmission corresponding to $v_t^{(j)}$ defined as the minimal SED between any two signal points whose binary labels disagree only in the j-th position and w_j stands for the Hamming distance between the two subsequences $(v_0^{(j)}, v_1^{(j)}, \ldots, v_t^{(j)}, \ldots)$ and $(\hat{v}_0^{(j)}, \hat{v}_1^{(j)}, \ldots, \hat{v}_t^{(j)}, \ldots)$ collected from $\underline{v}$ and $\hat{\underline{v}}$, respectively. Due to the bit-wise interleaver in Fig. 1, the minimum SED is obtained by

$$\left(\sum_{j=0}^{m-1} w_j\right) \cdot \min_{0 \leq j \leq m-1} d_j^2. \tag{6}$$

Since the PEPs with small SED dominate the BER in (4) at high signal-to-noise ratio (SNR), studies in [3][4] suggest that BICM-ID systems should be designed to maximize the minimum SED in (6) for obtaining a better BER performance.

2) EXIT Chart Based Analysis: For BICM-ID systems, the EXIT chart consists of two curves which describe how the mutual information between the LLRs and coded bits transfers from the input to the output of the decoder and demapper, respectively. Let $(I_A^{(\phi)}, I_E^{(\phi)})$ and $(I_A^{(\psi)}, I_E^{(\psi)})$ denote the pairs of mutual information of the decoder and demapper mentioned above. Based on the assumption of independent and equiprobable binary inputs for the channel encoder and signal mapper in Fig. 1, the average mutual information $I_E^{(\phi)}$ and $I_E^{(\psi)}$ of the decoder and demapper can be obtained respectively by [8]

$$I_E^{(\phi)} = \frac{1}{n} \sum_{i=0}^{n-1} I_{E,i}^{(\phi)} \quad \text{and} \quad I_E^{(\psi)} = \frac{1}{m} \sum_{j=0}^{m-1} I_{E,j}^{(\psi)} \tag{7}$$

where $I_{E,i}^{(\phi)}$ is the bit-wise mutual information between the output LLRs and the corresponding coded bits in the i-th output stream of the encoder and $I_{E,j}^{(\psi)}$ is the bit-wise mutual information between the output LLRs and coded bits in the j-th input stream of the signal mapper. Based on the analysis in [9]-[13], BICM-ID systems should be designed in a best way such that a tunnel between the decoder and demapper curves is opened at SNR as low as possible to guarantee a low threshold and the demapper and decoder curves should intersect at a point with mutual information as high as possible to avoid the undesired error floor at high SNR.

III. Performance Enhancement of the BICM-ID Systems via Protection Matching

By the discussion in Section II, many good BICM-ID systems have been constructed in the literature. Although those systems can achieve the desirable BER performance, we observe that a further improvement can be obtained with the aid of protection matching. For example, consider the BICM-ID system consisting of the $(5,2)$ convolutional code with the following generator matrix [16]:

$$G(D)=\begin{pmatrix}1 & 0 & 1 & 0 & D\\ 0 & 1 & D & 1+D & 1+D\end{pmatrix}$$

as the channel code, the signal mapper equipped with the set-partitioning (SP) labeling function μ_{sp} [3] on the 8PSK constellation:

$$\begin{array}{lll}\mu_{\text{sp}}(000)=1 & \mu_{\text{sp}}(001)=e^{j\pi/4} & \mu_{\text{sp}}(010)=e^{j\pi/2}\\ \mu_{\text{sp}}(011)=e^{j3\pi/4} & \mu_{\text{sp}}(100)=-1 & \mu_{\text{sp}}(101)=e^{j5\pi/4}\\ \mu_{\text{sp}}(110)=e^{j3\pi/2} & \mu_{\text{sp}}(111)=e^{j7\pi/4} & \end{array}$$

and a uniform bit-wise interleaver of block length 4800 bits. In this case, we have $n=5$, $k=2$, $m=3$, and $M=8$. Let $\underline{c}^{(i)}=(c_0^{(i)},c_1^{(i)},\ldots,c_t^{(i)},\ldots)$ be the i-th output stream of the channel encoder, $\forall\ 0\le i<5$, and denote by $\underline{v}^{(j)}=(v_0^{(j)},v_1^{(j)},\ldots,v_t^{(j)},\ldots)$ the j-th input stream of the signal mapper, $\forall\ 0\le j<3$. For the original design of BICM-ID systems in Fig. 1, the coded bits can be fed into arbitrary input streams of the signal mapper due to the uniform intereleaver. However, from the BER curves of $\underline{c}^{(i)}$'s and $\underline{v}^{(j)}$'s in Fig. 2, we observe that the channel encoder can provide 2 levels of protection for $\underline{c}^{(i)}$'s and the signal mapper can support 3 levels of protection for $\underline{v}^{(j)}$'s. Based on the idea of protection matching, we require that the coded bits in $\underline{c}^{(0)}$, $\underline{c}^{(2)}$, and $\underline{c}^{(4)}$ can be only fed into the input streams of the signal mapper corresponding to $\underline{v}^{(0)}$ and $\underline{v}^{(1)}$ and the coded bits in $\underline{c}^{(1)}$ and $\underline{c}^{(3)}$ can be only fed into the input streams of the signal mapper corresponding to $\underline{v}^{(1)}$ and $\underline{v}^{(2)}$. Revealed from the simulation results with 10 iterations for decoding in Fig. 3, the new design with protection matching can achieve about 4.5 dB gain at BER 10^{-5} than the original design. Below, the analytical tools introduced in Section II are used to explain why the new design can acquire better BER performance.

A. From BER Based Analysis

To measure the different protection levels provided by $G(D)$, we employ the free-output distance for the i-th output stream of the convolutional encoder originally proposed in [16] with the following definition:

$$d_{\text{free}}^{\text{out}(i)}=\min_{\underline{c}^{(i)}\ne\hat{\underline{c}}^{(i)}} d_H(\underline{c},\hat{\underline{c}}),\ \forall\ 0\le i<n \tag{8}$$

where $d_H(\underline{c},\hat{\underline{c}})$ is the Hamming distance between $\underline{c}$ and $\hat{\underline{c}}$. In general, the larger $d_{\text{free}}^{\text{out}(i)}$ is, the lower BER of $\underline{c}^{(i)}$ is. For the signal mapper, the SIED mentioned in Section II-B1 also plays an important role to indicate the protection levels on its input stream, for which the larger d_j^2 is, the higher protection $\underline{v}^{(j)}$ experiences. By (8), the free-output distances of $G(D)$ $(d_{\text{free}}^{\text{out}(0)},d_{\text{free}}^{\text{out}(1)},d_{\text{free}}^{\text{out}(2)},d_{\text{free}}^{\text{out}(3)},d_{\text{free}}^{\text{out}(4)})=(3,6,3,6,3)$. Also, for the signal mapper with μ_{sp} and the 8PSK constellation, the SIEDs $(d_0^2,d_1^2,d_2^2)=(4,2,0.586)$. The 2 and 3 distinct values in the free-output distances and the SIEDs, respectively, are also consistent with the observation of multilevel protection in Fig. 2. In the original design, by (6) the minimum SED is $3\times0.586=1.758$ due to the random data flow between the channel encoder and signal mapper. However, in the new design, the minimum SED becomes $\min(3\times2,3\times2+3\times0.586)=6$ owing to the constraint of protection matching. Since the minimum SED dominates the BER of the BICM-ID system, the new design with an enlarged SED can hence attain better BER performance.

B. From EXIT Chart Based Analysis

Since the data streams with different protection levels lead to different transfer curves in the EXIT chart, it is intuitively to observe these curves separately in the new design. For $0\le i<5$ and $0\le j<3$, the transfer curves $T_i^{(\phi)}$ and $T_j^{(\psi)}$ corresponding to $\underline{c}^{(i)}$ and $\underline{v}^{(j)}$ are plotted in Fig. 4, respectively. For the original design, the system performance may be dominated by the worst case determined by the intersection of $T_4^{(\phi)}$ and $T_2^{(\psi)}$ due to the uniform interleaver. However, by applying protection matching, the worst case is now determined by the intersection of $T_1^{(\phi)}$ and $T_2^{(\psi)}$ or the intersection of $T_3^{(\phi)}$ and $T_2^{(\psi)}$. Whatever the worst case will be, the intersection in the new design is always at a point with higher mutual information than the original design. The new design can thus offer more reliable transmission since the intersection of the decoder and demapper curves at a point with higher mutual information usually implies better BER performance.

C. General Guideline for Applying Protection Matching

The above example not only illustrates how to apply protection matching in practical implementation but also demonstrates the attainable benefit of the proposed design from the theoretical viewpoints. Because many well-designed BICM-ID systems are equipped with the channel encoders and signal mappers which can provide different protection levels, incorporating those systems with the idea of protection matching is expected to gain a further improvement in the BER performance. As described below, a general guideline for applying protection matching to BICM-ID systems is given.

Given a BICM-ID system, suppose the channel encoder and signal mapper can provide L and Q levels of protection, respectively. Let the coded bits be divided into L distinct sets $E_0,E_1,\ldots,E_{L-1}$ based on the corresponding protection level; bits in each set are expected to experience similar level of protection and assume that coded bits in E_i receive better protection than those in E_j, $\forall\ i<j$, without loss of generality. Similarly, denote by $S_0,S_1,\ldots,S_{Q-1}$ the sets of input streams of signal mapper, for which coded bits fed into the input streams of the signal mapper corresponding to S_i are assumed to receive better protection than those in S_j, $\forall\, i>j$. To apply the idea of protection matching, as illustrated in Fig. 5, an n-input L-output grouping unit is employed to divide the coded bits into $E_0,E_1,\ldots,E_{L-1}$ in accordance with the protection levels provided by the channel encoder. After permuting coded bits in each E_i by a proper interleaver Π_i with a shorter block length than Π in the original design, a two-step matching unit with L-input and m-output is then designed to schedule the data flow between Π_i's and the signal mapper. In the first step, all the coded bits from Π_i's are divided into Q sets $\Omega_0,\Omega_1,\ldots,\Omega_{Q-1}$; bits in each set are required to receive similar protection level, and bits in Ω_i are with better protection than those in Ω_j, $\forall\ i < j$. Then, the coded bits in Ω_i are fed into the input streams of the signal mapper corresponding to S_i, $\forall\ 0 \leq i < Q$. It deserves to be mentioned that protection matching only re-schedules the data flow between the channel encoder and signal mapper, the same demapper and decoder in the original BICM-ID receiver can still be employed in the new design without any modification. Moreover, conventional studies on the optimal design of channel codes, labeling functions, and interleavers [4][9][17] can be directly applied to the corresponding component blocks in the new design to achieve the optimal BER performance.

IV. Simulation Results

Besides the example shown in Section III, more simulation results are provided to verify the superiority of the new design. Firstly, consider the same convolutional encoder and 8PSK constellation in Section III but now with two different labeling functions: the Gray labeling μ_{Gray} and the semi-set-partitioning (SSP) labeling μ_{SSP} [4]. The BER curves of the original and new designs are plotted in Fig. 6. For the case of μ_{Gray}, the new system is observed to acquire 1 dB SNR gain over the original design at BER 10^{-5}. The reason for the better BER performance can be explained from the viewpoint of the EXIT chart, as shown in Fig. 7, in which the worst case of the intersection determined by $T_4^{(\phi)}$ and $T_2^{(\psi)}$ in the original design is now determined by $T_3^{(\phi)}$ and $T_2^{(\psi)}$ in the new design. A point with higher mutual information can hence be reached with the aid of protection matching to improve the BER performance. Similarly, for the case with μ_{SSP}, the new design can provide about 1.2 dB SNR gain over the original design at BER 10^{-5}. The corresponding EXIT chart in Fig. 8 also agrees with the BER curves since the worst case of the intersection determined by $T_4^{(\phi)}$ and $T_2^{(\psi)}$ in the original design is now determined by $T_3^{(\phi)}$ and $T_2^{(\psi)}$ in the new design.

Except for ordinary convolutional codes considered in the last example, protection matching can also provide performance improvement even for the BICM-ID systems with capacity approaching codes, e.g., turbo codes [18] and low-density parity-check (LDPC) codes [19]. For example, consider the BICM-ID system consisting of the LDPC code which provides 2 levels of protection with degree profiles $\rho(X) = 0.587X^6 + 0.413X^7$ and $\lambda(X) = 0.49X + 0.30X^2 + 0.1X^5 + 0.045X^6 + 0.0083X^{13} + 0.054X^{14}$ and the signal mapper with the 8PSK constellation. Assume that a uniform interleaver with block length 2046 bits and 25 iterations for decoding are used for simulation. With the aid of protection matching, simulation results in Fig. 9 show that the new design with μ_{Gray} and μ_{SSP} can acquire 0.5 dB and 0.75 dB SNR gain over the original design at BER 10^{-6}, respectively. It is worth mentioning that the previous works on the labeling design of BICM-ID suggest μ_{Gray} is more suitable than μ_{SSP} for the LDPC-coded BICM-ID system to achieve a lower threshold. However, owing to protection matching, the new design with μ_{SSP} outperforms the new design with μ_{Gray} at SNR=5.6 dB less than the original case and achieves a 0.5 dB SNR gain at BER 10^{-6}. In addition, protection matching has also been applied to BICM-ID systems in the fading channels and the multiple-input multiple-output (MIMO) environment with multidimensional labeling function and can still provide satisfactory performance improvement. Due to the length limitation, the corresponding theoretical analysis and simulation results are omitted.

V. Conclusions

In this paper, protection matching is proposed to improve the BER performance of the BICM-ID systems whose channel encoder and signal mapper are with the capability of multi-level protection. Not only theoretical analysis but also simulation results are given to verify the advantage of the proposed design. In addition, the idea of protection matching can also be applied to the BICM-ID systems in the fading channels and the MIMO environment with multidimensional labeling function for further performance improvement.

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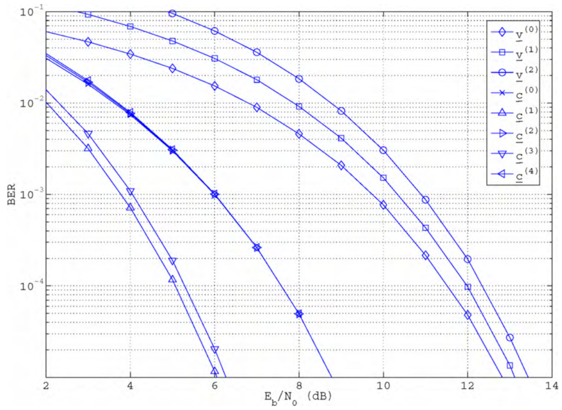

Fig. 2. BER curves of $\underline{c}^{(i)}$'s with BPSK modulation and $\underline{v}^{(j)}$'s with 8PSK modulation in AWGN channels, $\forall\ 0 \leq i < 5$, $\forall\ 0 \leq j < 3$.

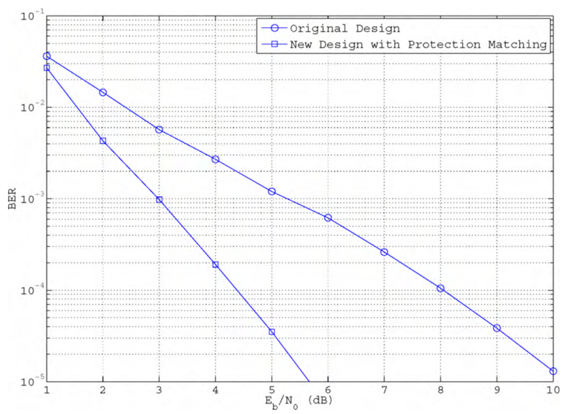

Fig. 3. Performance plots of the original design and the new design with protection matching in AWGN channels, where the set-partitioning labeling function is used and the number of iterations is 10.

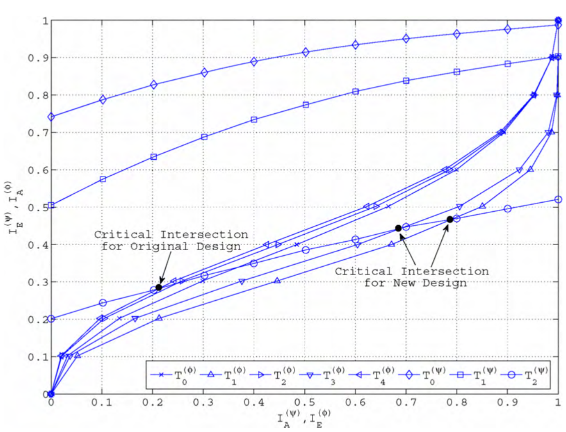

Fig. 4. EXIT chart of BICM-ID system with μ_{SP} at SNR $= 5$ dB in AWGN channels.

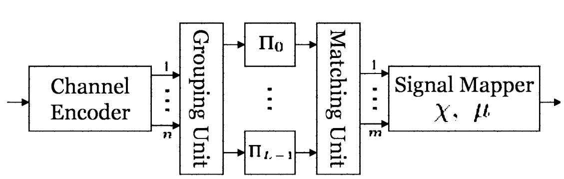

Fig. 5. Block diagram of BICM-ID transmitter with protection matching.

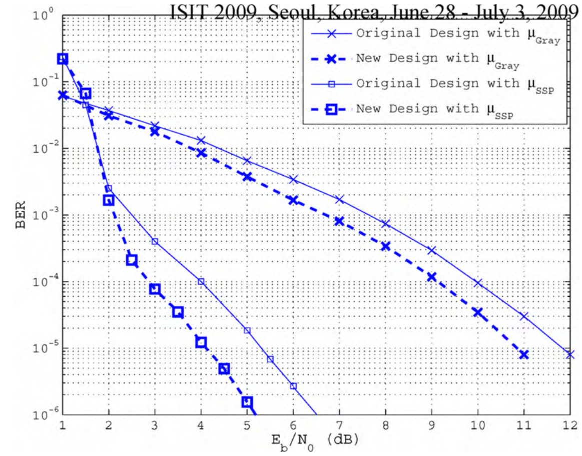

Fig. 6. Performance plots for various labeling functions in AWGN channels.

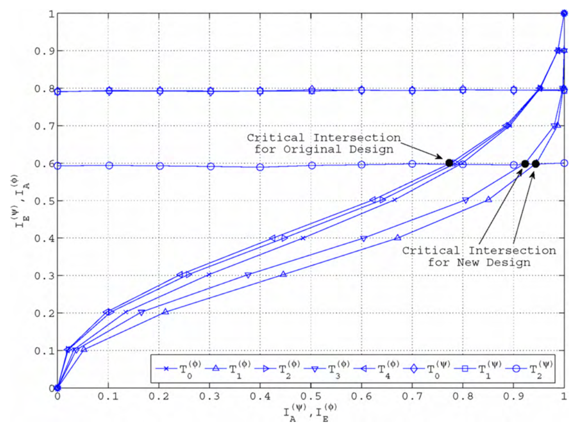

Fig. 7. EXIT chart of BICM-ID system with μ_{Gray} at SNR $= 6$ dB in AWGN channels.

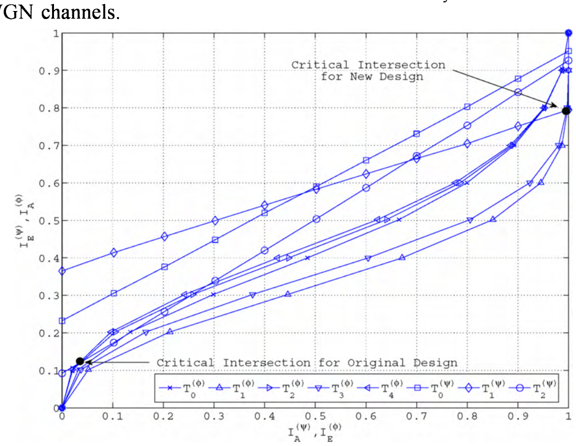

Fig. 8. EXIT chart of BICM-ID system with μ_{SSP} at SNR $= 3.25$ dB in AWGN channels.

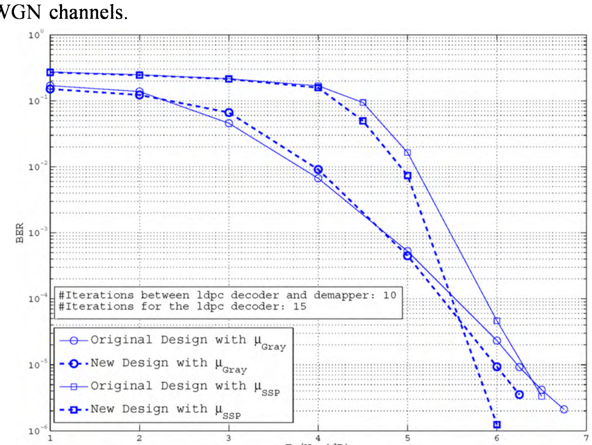

Fig. 9. Performance plots of the original LDPC-coded BICM system and the new design with protection matching in AWGN channels.